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On the Extension Theorem for Linear Codes (線形符号の延長定理について)

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Abstract. Hill and Lizak ([1]) proved that every $[n, k, d]_q$ code with $\gcd(d, q)=1$ and with all weights congruent to 0 or d (modulo q) can be extended to an $[n+1, k, d+1]_q$ code. We give another elementary geometrical proof of this theorem.

1. Introduction

An $[n, k, d]_q$ code \mathcal{C} means a linear code of length n with dimension k whose minimum Hamming distance is d over the Galois field $\text{GF}(q)$. The weight distribution of \mathcal{C} is the list of numbers A_i which is the number of codewords of \mathcal{C} with weight i . We only consider *non-degenerate* codes having no coordinate which is identically zero.

Let \mathcal{C} be an $[n, k, d]_q$ code with a generator matrix G . The code obtained by deleting the same coordinate from each codeword of \mathcal{C} is called a *punctured code* of \mathcal{C} . If there exists an $[n+1, k, d+1]_q$ code \mathcal{C}' whose punctured code is \mathcal{C} , \mathcal{C} is called *extendable* (to \mathcal{C}') and \mathcal{C}' is an *extension* of \mathcal{C} . Obviously, every $[n, 1, d]_q$ code is extendable.

As for the case when $k=2$, an $[n, 2, d]_q$ code \mathcal{C} is equivalent to the code with a generator matrix of the form

$$\begin{bmatrix} 1 \cdots 1 & 1 & \cdots & 1 & 1 & \cdots & 1 & \cdots & 1 & \cdots & 1 & 0 \cdots 0 \\ 0 \cdots 0 & \alpha & \cdots & \alpha & \alpha^2 & \cdots & \alpha^2 & \cdots & \alpha^{q-1} & \cdots & \alpha^{q-1} & 1 \cdots 1 \end{bmatrix},$$

where α is a primitive element of $\text{GF}(q)$. Let t_0, t_i ($1 \leq i \leq q-1$), t_q be the number of columns $[1 \ 0]^T, [1 \ \alpha^i]^T$ ($1 \leq i \leq q-1$), $[0 \ 1]^T$ respectively, so that $t_0 + t_1 + \cdots + t_q = n$. Setting $s = \max\{t_0, t_1, \dots, t_q\}$, we have $0 \leq t_i \leq s$ and $s = n - d$. So, \mathcal{C} is extendable iff there exists i ($0 \leq i \leq q$) with $t_i < s$. Since \mathcal{C} is an $[s(q+1), 2, sq]_q$ code iff $t_0 = t_1 = \cdots = t_q = s$, we get

Theorem 1. An $[n, 2, d]_q$ code \mathcal{C} is not extendable iff $n = s(q+1)$ and $d = sq$ for some integer s .

Although it is not so easy to find if an $[n, k, d]_q$ code is extendable or not when $k \geq 3$ in general, it is well known that every $[n, k, d]_2$ code with d odd is extendable (by adding an overall parity check). The following so-called extension theorem is a generalization of this fact.

Theorem 2. (Hill & Lizak [1])

Let \mathcal{C} be an $[n, k, d]_q$ code with the weight distribution $\{A_i\}$. If $\gcd(d, q)=1$ and if $i \equiv 0$ or $d \pmod{q}$ for all i with $A_i > 0$, then \mathcal{C} is extendable to an $[n+1, k, d+1]_q$ code \mathcal{C}' with the weight distribution $\{A'_i\}$ satisfying $i \equiv 0$ or $d+1 \pmod{q}$ for all i with $A'_i > 0$.

For an $[n, k, d]_q$ code \mathcal{C} with a generator matrix G , the *residual code* of \mathcal{C} with respect to a codeword c , denoted by $\text{Res}(\mathcal{C}, c)$, is the code generated by the restriction of G to the columns where c has a zero entry. The following lemma is well known for residual codes.

Lemma 3. Take $c \in \mathcal{C}$ with weight d . Then $\text{Res}(\mathcal{C}, c)$ is an $[n-d, k-1, d_0]_q$ code with $d_0 \geq \lceil d/q \rceil$, where $\lceil x \rceil$ is the smallest integer $\geq x$.

When q divides d , we can prove the following.

Theorem 4. An $[n, k, d]_q$ code \mathcal{C} is not extendable if q divides d and if $\text{Res}(\mathcal{C}, c)$ is an $[n-d, k-1, d_0]_q$ code with $d_0 = d/q$ for some $c \in \mathcal{C}$.

Example. Every $[q^2, 4, q^2 - q - 1]_q$ code \mathcal{C}_1 is extendable by Theorem 2 (see [1]). But the extension of \mathcal{C}_1 is not extendable by Lemma 3 and Theorem 4.

We give the proof of Theorems 2 and 4 in Section 3. A geometrical point of view (given in Section 2), which is a generalization of the above observation for the case when $k = 2$, is sometimes valid for linear codes (cf. [4],[5]). Although the original proof of Theorem 2 is elementary, we give another elementary geometrical proof to make clear the extendability of linear codes in the different way.

2. A geometric method

We denote by $\text{PG}(r, q)$ the projective geometry of dimension r over $\text{GF}(q)$. Assume $r \geq 2$. A j -flat is a projective subspace of dimension j in $\text{PG}(r, q)$. 0-flats, 1-flats, 2-flats, $(r-2)$ -flats and $(r-1)$ -flats are called *points*, *lines*, *planes*, *secundums* and *hyperplanes* respectively. We denote by \mathcal{F}_j the set of j -flats of $\text{PG}(r, q)$. The following lemma is a characterization of hyperplanes.

Lemma 5. Let F be a proper subset of $\Sigma = \text{PG}(r, q)$. Then F is a hyperplane of Σ iff every line in Σ meets F in one point or in $q+1$ points.

Proof. Assume that every line in $\Sigma = \text{PG}(r, q)$ meets a proper subset F of Σ in one point or in $q + 1$ points. Let l_0 be a line in Σ . Then we can find a point $Q_0 \in F$ on l_0 . Let δ_{j-1} be a $(j-1)$ -flat included in F , $1 \leq j \leq r-1$. Taking a line l_j which is skew to δ_{j-1} , we can get a point $Q_j \in F$ (on l_j) not on δ_{j-1} . Since every line through Q_j and a point of δ_{j-1} meets F in $q + 1$ points, we get $\delta_j = \langle Q_j, \delta_{j-1} \rangle \in \mathcal{F}_j$ included in F . Inductively, we get a hyperplane δ_{r-1} included in F . If a point $Q \in F$ not in δ_{r-1} exists, then we have $F = \langle Q, \delta_{r-1} \rangle = \Sigma$, a contradiction. Hence we obtain $F = \delta_{r-1}$. The converse is trivial. \square

Let \mathcal{C} be a (non-degenerate) $[n, k, d]_q$ code. The columns of a generator matrix of \mathcal{C} can be considered as a multiset of n points in $\Sigma = \text{PG}(k-1, q)$ denoted also by \mathcal{C} . We see linear codes from this geometrical point of view. An i -point is a point of Σ which has multiplicity i in \mathcal{C} . Let C_i be the set of i -points in Σ . For any subset S of Σ we define

$$c(S) = \sum_{i=1}^{\gamma_0} i \cdot |S \cap C_i|,$$

where γ_0 is the maximum of the multiplicities of points in Σ .

A line l with $t = c(l)$ is called a t -line. A t -plane, t -secundum and a t -hyperplane are defined similarly. Then we obtain the partition $\Sigma = C_0 \cup C_1 \cup \dots \cup C_{\gamma_0}$ such that

$$(2.1) \quad c(\Sigma) = n,$$

$$(2.2) \quad n - d = \max\{c(\pi) \mid \pi \in \mathcal{F}_{k-2}\}.$$

Conversely such a partition of Σ as above gives an $[n, k, d]_q$ code in the natural manner if there exists no hyperplane including the complement of C_0 in Σ . Since an $[n+1, k, d+1]_q$ code also satisfies (2.2) we get the following.

Lemma 6. An $[n, k, d]_q$ code \mathcal{C} is extendable iff there exists a point $P \in \Sigma$ such that $c(\pi) < n - d$ for all hyperplanes π through P .

We give an elementary proof of Theorem 2 using Lemma 6.

3. Proof of Theorem 2 and Theorem 4

Note that the number of i -hyperplanes is $A_{n-i}/(q-1)$ ($0 \leq i \leq n-d$). So, the condition ' $i \equiv 0$ or $d \pmod{q}$ for all i with $A_i > 0$ ' in Theorem 2 implies that $c(\pi) \equiv n$ or $n-d \pmod{q}$ for all $\pi \in \mathcal{F}_{k-2}$.

Proof of Theorem 2. Put $F = \{\pi \in \mathcal{F}_{k-2} \mid c(\pi) \equiv n \pmod{q}\}$. For any t -secundum δ of $\Sigma = \text{PG}(k-1, q)$, denote by a_δ (resp. b_δ) the number of hyperplanes π through δ with $c(\pi) \equiv n \pmod{q}$ (resp. $c(\pi) \equiv n-d \pmod{q}$). Then we have $a_\delta + b_\delta = q+1 \equiv 1$ and $(n-t)a_\delta + (n-d-t)b_\delta + t \equiv n$, so that $d(a_\delta - 1) \equiv 0 \pmod{q}$. Since $\gcd(d, q)=1$, we get $a_\delta \equiv 1 \pmod{q}$, whence $a_\delta = 1$ or $q+1$. This implies that every line in a dual space Σ^* meets F in one point or $q+1$ points. By Lemma 5, F is a hyperplane of Σ^* , whence there exists a point $P \in \Sigma$ such that the set of all hyperplanes through P is equal to F . Since $c(\pi) \equiv n \pmod{q}$ implies $c(\pi) < n-d$, \mathcal{C} is extendable by Lemma 6. By adding P to the multiset \mathcal{C} , we get an extension of \mathcal{C} which satisfies $c(\pi) \equiv n+1$ or $n-d \pmod{q}$ for all $\pi \in \mathcal{F}_{k-2}$. \square

It follows from the above proof that the point to be added to the multiset \mathcal{C} to get an extension of \mathcal{C} is uniquely determined under the condition of Theorem 2.

Proof of Theorem 4. Since $\text{Res}(\mathcal{C}, c)$ is an $[n-d, k-1, d/q]_q$ code for some $c \in \mathcal{C}$, there exists a t -secundum δ with $t = n-d-d/q$ in $\Sigma = \text{PG}(k-1, q)$. Considering the hyperplanes through δ , we have

$$n \leq (n-d-t)(q+1) + t = n,$$

whence every hyperplane through δ is a $(n-d)$ -hyperplane. Hence every point in Σ is on a $(n-d)$ -hyperplane, and \mathcal{C} is not extendable by Lemma 6. \square

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